ASSESSING CORRELATION OF HUMAN RESPONSE TO VIBRATION THROUGH VIBROTACTILE THRESHOLD SHIFT WITH VIBRATION EXPOSURE DETERMINED ON THE SUBJECT

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Abstract

Existing risk assessment methodologies are based on fixed tool vibration magnitude emission data and tool usage time. The research evaluates the relationship between vibration dose assessment on subjects using wearable sensors with temporary threshold shift (TTS) in vibrotactile perception. Human response to vibration, using TTS perception response, in male subjects (n = 12) exposed to hazardous vibration was undertaken. Simultaneous vibration measurements were undertaken on the subject and conventional measurements at the tool hand-grip interface in accordance with ISO 5349-2. Two modes of tool operation (drill and impact) and two postures (horizontal and vertically downwards) of tool use were considered. The results demonstrate a stronger relationship between the hand transmitted vibration determined by the wearable sensor on the subjects and the human response to the vibration over the conventional measurement on the tool. It could be further hypothesised that control measures derived from in-use tool data would be more effective in reducing the underlying risk to operatives.

1. Introduction

Hand-arm vibration syndrome (HAVS) is a recognised industrial disease induced by excessive exposure to vibration through occupational tasks involving vibrating machinery (Bovenzi, 1998). HAVS comprises a range of disorders affecting the peripheral circulatory system, peripheral nervous system and muscular skeletal system of the hand and arm. As a progressive and irreversible condition, the ability to predict a rate of progression and take timely preventative action through exposure reduction or complete elimination of hazardous exposure is highly desirable. However, reliable dose response relationships have proved elusive. This is in part due to the difficulties in acquiring sufficiently reliable exposure and epidemiological evidence and in part due to the fundamental shortcomings in the existing exposure assessment methodologies.

The established method for assessing exposure has been standardised in the form of ISO 5349 (BSI, 2001a) with employers being required to control exposure levels to predetermined limits within their

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respective territorial legislation. Despite the existence of international standards concerning exposure assessment and regional legislation regarding working practices, reported cases of HAVS remain significant as indicated by disability benefit claims in the UK (HSE, 2018). It should be noted that this data does not reflect all diagnosed cases of the conditions, only those sufferers choosing to claim disability benefit from the UK Government. Since the condition typically takes many years to become symptomatic there is significant variation in the reported rate of progression relative to exposure. Defining an accurate response relationship is a significant challenge. The standards provide clear guidance on vibration magnitude measurements to be taken on the tool within the work place. However, compliant measurements are seldom undertaken frequently enough to adequately reflect the range of tool deployment in the work place. In research laboratory work it is common to determine exposure from a fixed vibration magnitude which has not been taken from the *in-situ* workplace use of the tool (Bovenzi, 2010, Tominaga, 2005, Mahmood et al., 2017, Su et al., 2011, Su et al., 2016, Griffin et al., 2003). The standard method for calculating exposure based on tool vibration emission requires skilled technicians to execute a repeatable assessment. In practise, this is unlikely to capture the effects of different posture, coupling force, operator physiology and the variability in day-to-day tasks undertaken by tool operators within different industry sectors. The CEN technical report CEN/TR 15350 (BSI, 2013) identifies the difficulties in capturing all the factors affecting the vibration level of a tool and recognises the expense in doing so. CEN/TR 15350 advises that the exposure to vibration does not only depend on the machine used but also to a large extent on the quality of inserted tools, the work situation and operator behaviour. It concludes that these factors must be considered to make an ideal assessment of vibration exposure.

In numerous industrial sectors, there are difficulties associated with obtaining a conventional vibration measurement on the tool at the workplace. This results in a common approach to HAV risk management being the use of tool manufacturer's declared vibration emission values. Guidance from the HSE illustrates the risk of using declared emission data for risk management and the likelihood of under estimating materially an individual's exposure (HSE, 2005 Page 64, section 216). CEN/TR 15350 identifies that uncertainty of the vibration value has more influence on the uncertainty of the daily vibration exposure than that of the duration and that the uncertainty of the vibration value in real use is normally much greater than the uncertainty factor declared by the manufacturer.

The effect of hand coupling action on vibration transmission through to the hand arm system has been undertaken in historical studies.. Maeda et al. (2007) investigated the effect of hand coupling actions on the TTS of vibrotactile perception, illustrating that hand coupling actions affect the human response. Maeda and Shibata (2008) also provided evidence of the effect of operative posture on TTS results. Further research to examine operator physiology and biodynamics is required to fully understand the response of structures within the hand and arm to mechanical vibration.

The sensitivity of mechanoreceptors can be significantly reduced by long-term exposure to hand-transmitted vibration (Brammer et al., 1987). For this reason, the measurement of finger vibration perception threshold (VPT) has been viewed as an important approach and has been widely used to diagnose and investigate hand-arm vibration syndrome (HAVS). The method has been standardized by the International Organization for Standardization (BSI, 2001b). Previous studies (Bjerker et al., 1972, Hahn, 1966, Lundström and Johansson, 1986) have also shown that after a person is exposed to hand-transmitted vibration, the vibration perception threshold could be temporarily increased and it could take some time (usually greater than 10 minutes) for the VPT to come back to its normal value, which is conventionally termed as temporary VPT shift (TTS). Lidström et al. (1982)found that the magnitude of the TTS was higher for workers exposed to long-term hand-transmitted vibration than for age-matched controls. Radzyukevich (1969) suggested that the temporary threshold shift (TTS) in vibrotactile perception threshold at the end of a working day correlated with the permanent threshold shift (PTS). Malinskaya et al. (1964) found that the mean TTS of workers after a day of work that included vibration exposure corresponded to the PTS of vibratory sensation that occurred in the group after 10 years of exposure. These observations suggest that the TTS after daily exposure may be used as a measure to indicate the PTS after prolonged exposure to vibration. Therefore, TTS may be used as a convenient and relevant index to investigate the effects of the vibration exposure and influencing factors on the development of finger nerve disorders.

Experiments were performed to examine the relationship between the human response to vibration determined by the TTS of subjects, and the in-use hand transmitted vibration as determined by a wearable sensor. Conventional measurements of vibration emission on the tool grip were performed concurrently as a control reference. From this experiment the suitability of a wearable technology for determining HAV exposure risk is considered relative to in-use testing on the tool and fixed data, such as declared vibration magnitude.

2. Experiment

2.1. Human test subjects

Tool vibration data was obtained from a series of controlled tests performed using a standard industrial power tool in a laboratory setting. Twelve healthy male subjects between 18 and 24 years of age with no previous history of vibration exposure were selected as subjects. Alcohol, nicotine and caffeine intake were prohibited prior to and for the duration of the test protocol in accordance with ISO 13091-1 (BSI, 2001b). Screening was undertaken to ensure that all participants were clear of medical conditions that would have an impact upon the research. The experimental method was approved by the Edinburgh Napier University research ethics committee, all subjects were willing volunteers and individual consent was obtained prior to commencing the experiments.

2.2. Tools and in-use postures

A single mechanized hand tool was used during the course of the experiments with variable speeds and action settings. Tool specification and operating descriptions are provided in Table 1.

Table 1 Tool specification.

	Setting 1	**Setting 2**
Tool description	Drill	Hammer drill
Mechanical action	Rotary	Impact
No Load Speed	400 rpm	6000 blows / min
Mass (kg)	1.7	1.7

To assess the role different postures and subjects have on the human response relative to the two respective dose assessment methods, two postures were considered. These were horizontal and vertically downwards. A reaction frame was constructed to allow a 450 x 450 mm x 50 mm concrete test panel to be mounted in the two configurations. The reaction frame ensured that the correct posture was attained and that structural resonance from the substrate were minimized. Figure 3 shows the general arrangement of the reaction frame, the two posture configurations and the location of a force plate.

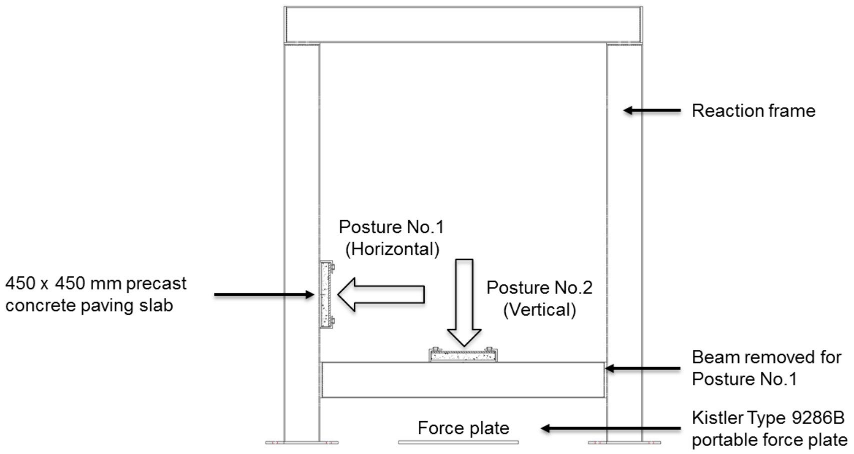

Figure 1 Reaction frame configuration showing postures and force plate location.

The postures illustrated in Figure 1 were considered for the investigation as those commonly employed when operating a hand-held drill. Figure 2 further illustrates the positions of use and the position of the human subject and the force plate.

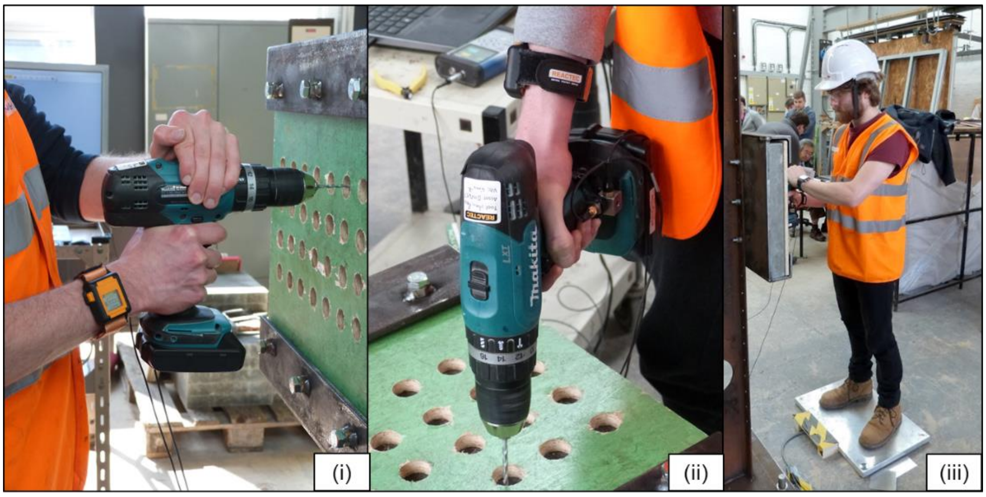

Figure 2 Test postures (i) horizontal (ii) vertical downwards and (iii) force plate location.

Push force for each of the tool tests was controlled through the use of a force plate (Kistler 9286B) mounted on concrete and a digital display to ensure a steady 50 N force was applied against the work test panel. Figure 2 (iii) shows a test subject standing on the force plate while applying the tool to the substrate affixed to the reaction frame in posture 1. Subjects applied the tool to the substrate continuously, only removing it when required to start a fresh hole in the concrete substrate.

2.3. Experimental conditions

All subjects were given induction training on how to operate and grip each tool. However, subjects were not experienced tool operators and demonstrated a degree of variability in tool operation performance. Grip force was not monitored. Prior research examining the effects of grip force for vibration transmission (Maeda et al., 2007) concluded that grip force was not considered to be significant providing a grip force of at least 30 N was attained. Tool vibration emission data during two minutes was measured using two ISO 8041 compliant reference instruments; a Svantek SV106 and a Brüel & Kjær Photon+ with RT Pro software. The devices were configured to obtain a continuous two-minute duration measurement. Two accelerometers were attached to the tool hand grips. A Svantek SV150 and Brüel & Kjær 4520-001 were used as shown in figure 3.

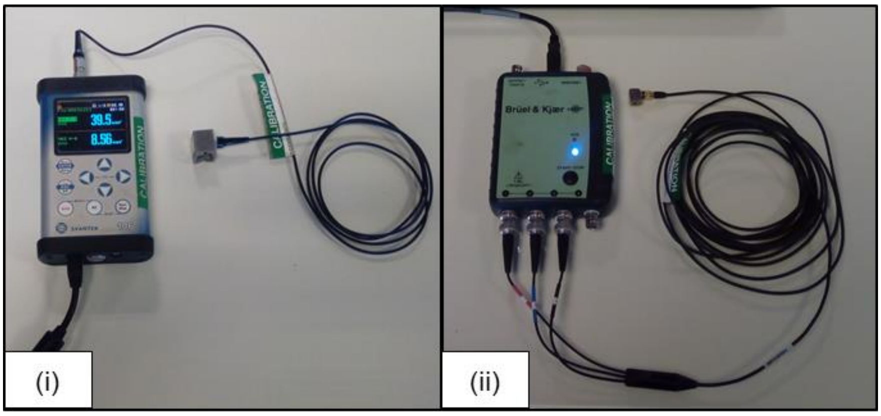

Figure 3 Tool emission instrumentation (i) Svantek SV106 & SV 150 accelerometer (ii) Brüel & Kjær Photon+ 4520-001 accelerometer.

3. Methods of Vibration Dose Measurement

3.1. Vibration dose measurement on tool

Tool vibration emission data measurement equipment is defined by the standard ISO 8041 (BSI, 2017). In working environments, the hand-arm vibration dose from the tool handle to the operative follows the ISO 5349-2 (BSI, 2015) standard by using the measurement equipment compliant with ISO 8041. In accordance with ISO 8041 the frequency-weighted root-mean-square (r.m.s.) vibration acceleration value in a specified axis, a_{hw}, is defined by the following expression:

$$a_{hw} = \left(\frac{1}{T} \int_0^T a_{hw}(t)^2 dt \right)^{1/2} \qquad \text{Equation 1}$$

Where $a_{hw}(t)$ is the frequency-weighted vibration acceleration in a specified axis as a function of the instantaneous time, t, in meters per second squared (m/s^2). T is the duration of the measurement.

The combined vibration from the three axes x, y and z is defined by the following expression:

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \qquad \text{Equation 2}$$

Where a_{hwx}, a_{hwy} and a_{hwz} are the weighted vibration values in the three orthogonal axes x, y and z.

3.2. Wearable sensor dose measurement on subject

Annex D of the ISO 5349-1 standard identifies a number of factors which will impact the hand transmitted vibration magnitude. This could be represented mathematically such that when the tool handle vibration magnitude is '*a*', the hand-transmitted vibration magnitude may be defined by the following equations:

$$a_{HTVx} = a_x H_{FW} Ha_x Hb_x Hc_x Hd_x He_x Hf_x Hg_x Hh_x Hi_x Hj_x Hk_x Hl_x \qquad \text{Equation 3}$$

$$a_{HTVy} = a_y H_{FW} Ha_y Hb_y Hc_y Hd_y He_y Hf_y Hg_y Hh_y Hi_y Hj_y Hk_y Hl_y \qquad \text{Equation 4}$$

$$a_{HTVz} = a_z H_{FW} Ha_z Hb_z Hc_z Hd_z He_z Hf_z Hg_z Hh_z Hi_z Hj_z Hk_z Hl_z \qquad \text{Equation 5}$$

Where Ha_x is the transfer function of factor *a* in the x-axis and so on. H_{FW} is the frequency weighting defined by ISO 5349-1. These equations take all affecting factors into the tool handle vibration magnitude '*a'*.

The effect of an individual factor on vibration magnitude may be studied experimentally in isolation. For example, the transmission factor of *He* of coupling force was examined by Pan et al. (2018) and Kaulbars (1996) in laboratory conditions. Also, Pan et al. (2018) established that the coupling action influenced the vibration transmission to the wrist from the tool handle emitted vibration but did not model this as an *He* weighting coefficient.

If the individual factors or some combination of factors from Annex D of ISO 5349 are not modelled, then a properly conducted measurement of the emitted vibration from the tool handle will carry remaining uncertainties as to the vibration magnitude transmitted to the hand. In moving the measurement point to the recipient of the vibration it is believed that the effects of at least some of the factors influencing equations 3, 4 and 5 above can be considered in the determination of the hand transmitted vibration.

Vibration on the subject was measured using a wrist mounted industrial wearable device (HVW-001, Reactec Ltd.). The device is mounted to the wrist by way of an adjustable nylon webbing strap, adjusted and fastened by way of velcro loop arrangement. The device features a three axis MEMS accelerometer sampling at 1.6kHz for 0.66 seconds every 1.5 seconds. A frequency range from 3Hz to 650Hz is captured. Acceleration data from each axis is converted independently from time domain to frequency domain through a Fourier analysis incorporating a Hanning window function to generate discrete magnitude values for each axis (Maeda et al., 2017). Acceleration a_{rhv} is calculated using the following formula.

Transformed vibration magnitude for x - axis during iteration n:

$$a_{rhx}(n) = \sqrt{\sum_{i} w_{rhx}(i)^2 . a_{hx}(n,i)^2} \quad \text{Equation 5}$$

$w_{rhx}(i)$ is the i_{th} frequency dependent transfer function for the x – axis.

Similar definitions are derived for axis y and z axes:

$$a_{rhy}(n) = \sqrt{\sum_{i} w_{rhy}(i)^2 . a_{hy}(n,i)^2} \quad \text{Equation 6}$$

$$a_{rhz}(n) = \sqrt{\sum_{i} w_{rhz}(i)^2 . a_{hz}(n,i)^2} \quad \text{Equation 7}$$

Running average (r.m.s.) 3 - axes vibration magnitude formula after iteration *n*:

$$a_{rhz} = \sqrt{\frac{\sum_n a_{rx}(n)^2}{n}} \quad \text{Equation 8}$$

$$a_{rhv} = \sqrt{a_{rhx}^2 + a_{rhy}^2 + a_{rhz}^2} \quad \text{Equation 9}$$

Where, $w_{rhx}(i)$, $w_{rhy}(i)$ and $w_{rhz}(i)$ are the transfer functions from the tool handle to the wrist calculated as below from a characterized transmissibility for each axis between a grip point incident vibration to a measured point on a human wrist. The idealized transfer function $w_{rhx}(i)$, $w_{rhy}(i)$ and $w_{rhz}(i)$ are derived by the calculations:

$w_{rhx}(i)$ = (ISO 5349-1 frequency weighting) / (x-axis of measured transmissibility on the Wrist)

$w_{rhy}(i)$ = (ISO 5349-1 frequency weighting) / (y-axis of measured transmissibility on the Wrist)

$w_{rhz}(i)$ = (ISO 5349-1 frequency weighting) / (z-axis of measured transmissibility on the Wrist)

The transmissibility between the tool user interface and the accelerometer within the wearable sensor was determined by the device manufacturer by assessing the transmission of input vibration energy across a defined frequency spectrum in the three orthogonal axes. Three-dimensional input vibration energy was generated utilising three 1-D shakers (MB Dynamics) arranged along the three orthogonal axis. A random broad band signal was employed across a frequency range of 10-500Hz. Vibration amplitude was maintained throughout the duration of the characterisation process by means of a closed loop control system at a 1G level. The vibration was delivered to the human hand through an instrumented handle coupled with each shaker using a flexible linkage system. The control system utilised vibration data from the instrumented handle to ensure correct vibration magnitude was maintain in each axis throughout the test cycle. The instrumented handle was equipped with a tri-axial accelerometer (Endevco, 65-100) and a pair of force sensors (Interface, SML-50) for measuring the acceleration at the user interface and applied grip force. A force plate (Kistler, 9286AA) was used to measure the push force applied to the handle. The applied and target grip and push forces were displayed on two virtual dial gauges on a computer monitor in front of the subject. The subjects were instructed to control the grip force and push force to 30N and 50N respectively. An additional accelerometer (Endevco, M35A) was attached to the subjects' skin using I.V. needle adhesive tape adjacent to the wearable sensor to provide additional reference data.

Applying the protocol described above a series of 6 characterisations were conducted on each test subject. Each characterisation was conducted continuously for a duration of 1 minute. For the purposes of this initial detailed characterisation subjects were limited to N=3. Normative data from the above series of characterisation was used to derive a mean transmissibility for each axis. Transmissibility was seen to reach an effective minimum in all axis above 500Hz therefore characterization beyond this frequency was not deemed necessary.

By way of demonstrating the effectiveness of the wearable sensor to determine the vibration required to assess HAV exposure through transformation of a measurement taken on the subject's wrist, figures 4 and 5 illustrate the frequency spectrum of vibration magnitude for a measurement taken on the tool in compliance with ISO5349 and that determined by the wearable sensor for each of the two tool settings used in the experiment of this paper.

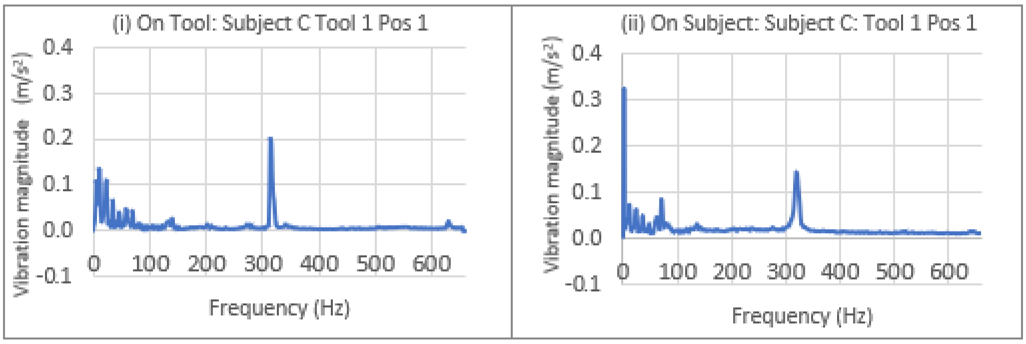

Figure 4 Tool setting No.1 (drill), posture 1 – (i) frequency response on tool and (ii) frequency response on subject.

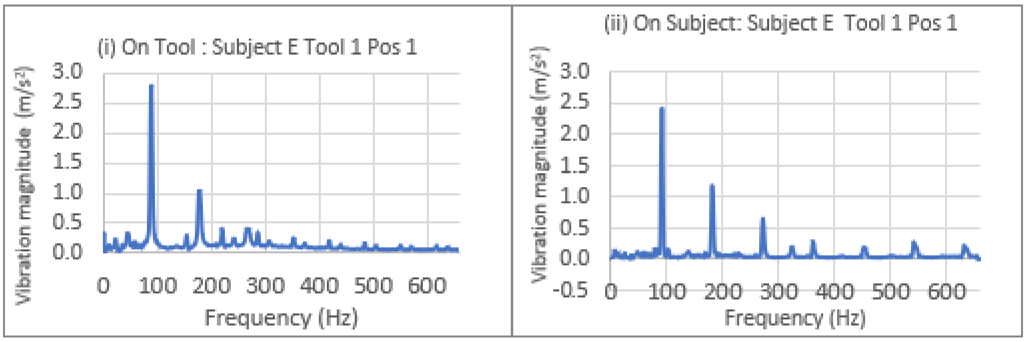

Figure 5 Tool setting No.2 (impact drill) – (i) frequency response on tool and (ii) frequency response on subject.

While there is an intention to further refine the transfer function to address more of the factors identified in equations 3,4 and 5, at this stage, the transfer function developed from the average transmissibility to the wrist of the three male subjects was used for demonstrating the effectiveness of the wearable sensor's dose measurement in the presented study. An experiment was designed to indicate whether the wearable sensor, while mounted at the wrist, is effective in measuring the hand-transmitted vibration.

3.3. Assessment of vibrotactile temporary threshold shift (TTS)

VPT was assessed on each individual subject for each tool test. A VPT test was undertaken three minutes prior to commencing the tool activity test and within thirty seconds of completing the two minute tool activity test. The VPT of 125 Hz was measured at the tip of the index finger of the right hand. A vertical force was maintained by mounting the vibration exciter on digital scales. The subjects were asked to maintain 0.20 kg by monitoring the value on the digital display. Vibration thresholds were determined using a RION type AU-02A vibrotactile sensation meter by means of gradually increasing and decreasing vibration source noting the level at which it becomes perceptible by the subject. Thresholds were calculated by the mean values of three measurements obtained over a period not exceeding thirty seconds. The TTS was defined as the difference (dB) of the vibrotactile thresholds before and after vibration exposure (Yonekawa et al., 1998). Subjects were limited to two vibration test sessions per day with a minimum of four hours rest between each test.

The TTS was calculated by the following equation.

$$TTS\ (dB) = VPT_A - VPT_B \quad \text{Equation 10}$$

where, VPT_A(dB) is the vibrotactile perception threshold after tool vibration exposure and VPT_B(dB) is the vibrotactile perception threshold before tool vibration exposure. The experiment protocol timeline is summarised in figure 6.

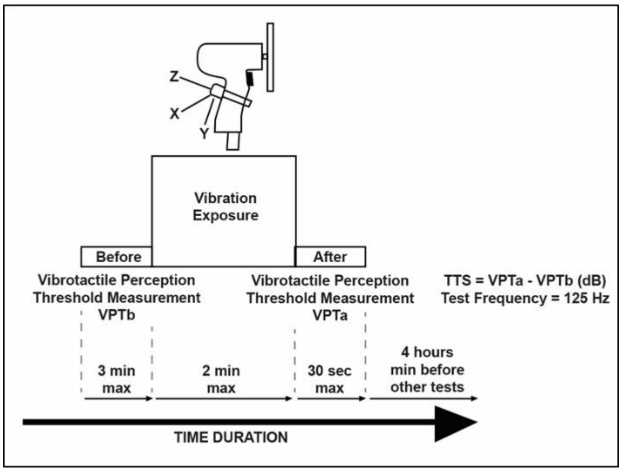

Figure 1 Test protocol timeline.

Ambient temperature within the test laboratory was maintained at 20°C +/- 4°C for the duration of all tests and subject fingertip temperature was measured and recorded during each TTS assessment. This was undertaken using a thermocouple attached to a digital display (RS 206-3738). A Grant 2020 Series Squirrel data logger with four thermocouples was used to monitor ambient air temperature throughout the duration of the tests. An industrial electric fan heater was used to maintain the ambient air temperature at approximately 20°C. VPT test apparatus is shown in figure 7.

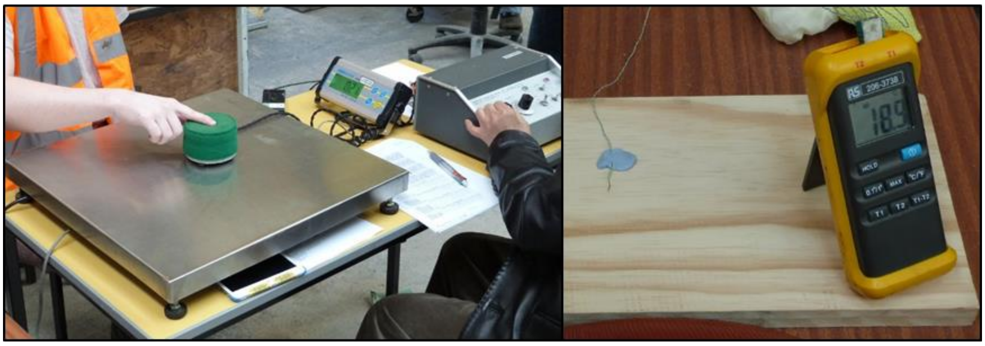

Figure 2 VPT assessment using vibratory sensation meter (Rion Company Ltd. Model AU-02A) and skin temperature thermocouple sensor (RS 206-3738).

Fingertip temperature was checked before and after VPT measurement. If the subject's fingertip temperature was lower than 23°C, the subject was instructed to warm their finger. During this experiment, all subject's fingertip temperature was over 25°C.

4. Results

Each test subject, a tool setting and a tool posture was conducted once in this experiment. All test results are included in the presented data with the exception of four results where there was inadequate triggering of the wearable sensor for tool setting No.1 (drill). Figure 8 (i) shows the relationship of TTS and the vibration magnitude on the tool handle. Figure 8 (ii) shows the relationship of TTS and the wearable sensor vibration magnitude, all for tool setting No.1 (drill) and in the horizontal posture (Posture No.1).

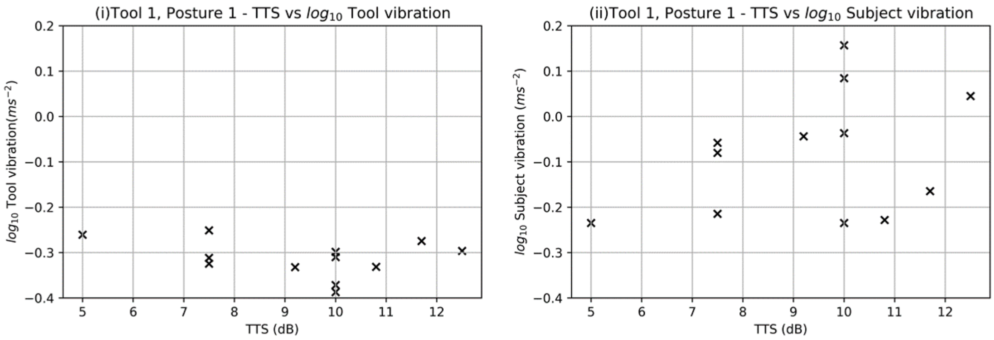

Figure 3 TTS results (i) tool vibration and (ii) subject vibration (Tool 1, Posture 1).

Figures 9 (i) shows the relationship for each subject between TTS and the vibration magnitude on the tool handle. Figure 9 (ii) shows the relationship for each subject between TTS and the wearable sensor vibration magnitude, for tool setting No.2 (impact drill) and in the horizontal posture.

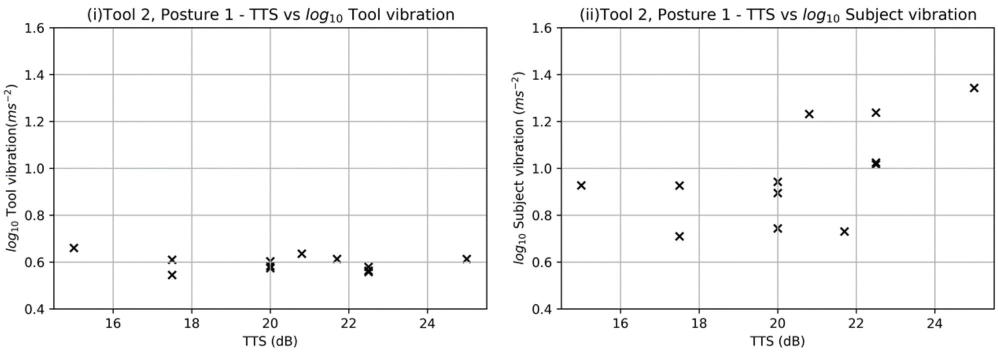

Figure 4 TTS results (i) tool vibration and (ii) subject vibration (Tool 2, Posture 1).

For both tool settings there is variation in the human response to vibration across the subjects while the measured vibration on the tool remains relatively constant. In contrast, the vibration transmitted to the subject determined by the wearable sensor trends more distinctly with the increased level of human response to vibration. Figure 10 provides TTS results for an individual subject illustrating the human response to the tools' vibration for the two different tool settings and two postures used for the tool.

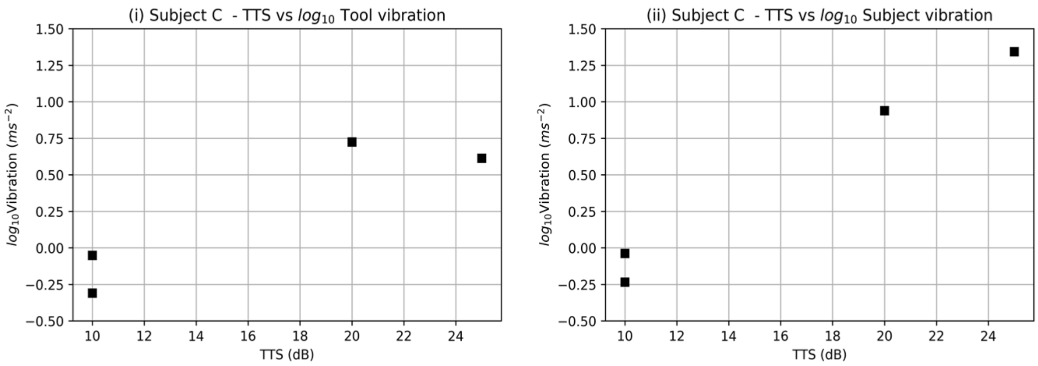

Figure 10 TTS results Subject C (i) tool and (ii) subject (tool 1 & 2, posture 1 & 2).

Figure 11 provides a summary of the all tests showing tool and subject vibration measurements.

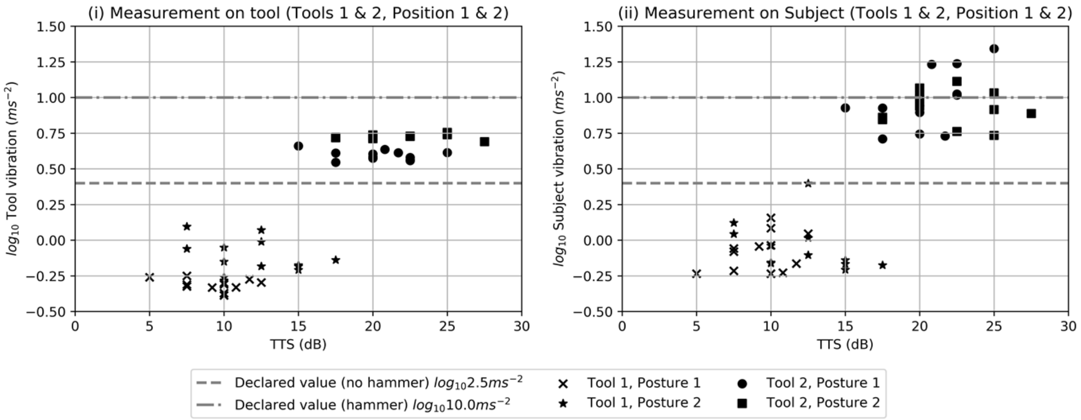

Figure 5 TTS vs (i) tool and (ii) subject vibration measurements for all tests. Manufacturers declared emission values of 2.5 ms-2 and 10.0 ms-2 provided for reference purposes

The in-use measurement of vibration on the tool has two distinct clusters between the two tool settings. While the range of human response to the vibration is distinctive between the two tool settings, within each tool setting the vibration magnitude measured on the tool remains essentially constant relative to the human response. A more proportional relationship of increasing human response with increasing magnitude is apparent in the determined vibration from the wearable sensor on the subject.

The tool used for the experiments has in total four settings based on two speeds and engagement of a hammer setting. In accordance with the ISO 28927-5 (BSI, 2017) standard, the manufacturer declares two vibration magnitudes for the tool depending on whether the hammer action is activated or not and was not prepared to advise on which speed setting was used for the declaration.

5. Discussion

Figure 11(i) shows that the tool vibration magnitude was relatively constant for the two different settings across the two postures and subjects. The human response as determined by the TTS of the individual subjects ranged over a wide scale for each of the two settings. Experimental results showed the TTS of the subjects varied significantly for each of the two tool settings across subjects and postures of tool use. However, the vibration magnitude measured on the tool handle, in compliance to ISO 5349, was essentially fixed for each tool setting. The measurement on the handle was therefore not able to reflect some of the factors which resulted in a different human response to the vibration.

Figure 11 (ii) shows a positive relationship between the human response to vibration of the subjects as determined by their TTS and the hand transmitted vibration magnitude determined by the wearable sensor. This may imply the wearable sensor on the wrist can measure the hand-transmitted vibration considering the affecting factors of Annex D of ISO 5349-1 standard. Further research is required to validate such measurement in industrial working environments. A specific test subject's result provided evidence of the wearable device vibration measurements correlating with the range of TTS results against the TTS relationship with the tool grip vibration measurements. The results presented show that there is a significant relationship between TTS results and the measurement of vibration exposure using a wearable monitoring device.

The results shown in figure 12 (i) support the issues highlighted in CEN/TR 15350 (2013) in that the exposure to vibration depends on things like the work situation and operator behaviour. These factors need to be taken into account to make an ideal assessment of vibration exposure. Figure 12(ii) suggests that a wearable sensor can distinguish between tool performance and operator behaviour in determining the hand transmitted vibration.

The results of this study show a distinct variability at an individual level on the human response to vibration and the potential for a wearable sensor to be able to distinguish more readily the vibration transmitted to the user and resulting risk. Consideration of the human response to vibration as measured with wearable measurement devices may help identify potential hazards and provide more satisfactory assessment of risk when compared to general tool emission assessments.

6. Conclusions

The research findings contribute to the development of wearable vibration exposure monitoring devices as a means of capturing authentic *in-situ* work environment operative exposure. The results presented demonstrate that the assessment of vibration transmitted to the operator using wearable technology is positively correlated with the human response as measured using TTS of vibrotactile response. Therefore use of vibration exposure measurement on the body represents a useful assessment of vibration exposure hazards and in sight to the working scenarios which contribute to the development of hand-arm vibration over exposure symptoms. The results show that tool vibration emission is potentially an unreliable method of assessing *in-use* tool vibration exposure as it fails to capture the effects that different operative posture and operative skill have on the human response. The practice of work environment controls based upon a point in time laboratory (or even work place) tool emission test data does not capture the possible range of work-face variables that contribute to operative vibration exposure. This may contribute to uncertainty relating to the assessment of risk based upon tool vibration emission magnitudes. Such uncertainty is likely to contribute to the continuing reporting of injury and illness associated with excessive and inadequately controlled vibration exposure.

7. References

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